Beams-doc-2060-v1
December 19, 2005

A Quick Look at MI BPM Flash Data

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Abstract

This note presents a first look at flash data from two injections within the same cycle. It shows that the flash measurements are working properly and discusses the response of the BPM system when it is measures a batch that is slipping during slip-stacking.

Contents

1 Introduction

The presented data in this note are flash data collected when the Main Injector was running a super-cycle containing many instances of MI state 28, which has a master reset of TCLK 0x29. This cycle does slip stacking of protons from the Booster, with the following steps:

- One batch is injected from the Booster into the MI.
  - This batch is nominally 80 bunches in consecutive buckets.
- Almost immediately after injection, the energy of the beam is lowered a little, moving the beam to an orbit with a smaller radius.
- During this operation, the RF signal sent to the timing module remains at the frequency of the central orbit.
  - Therefore one should see this batch slip with respect to the reference RF signal that arrives at the timing card.
- On the next 1/15 second tick of the booster cycle, a second batch is injected into the Main Injector. This batch is injected onto the central orbit.
- The first batch is kept on the smaller radius orbit until the two batches become lined up.
- At that time the two batches are captured into a single combined batch.
- The beam energy is ramped and the beam is delivered to the antiproton production target.
- Any residual beam is dumped.

For this study the front end computer was configured in state dependent mode. When the master reset for state 28 was received, the front end initialized the Echotek and timing card as follows:

- Set the Echotek to wide-band mode, measuring 53 MHz for 512 measurements.
- Tell the timing card to go into flash mode.
- Tell the timing card its pre-trigger delay, measured in turns, and its turn by turn delay, measured in half-buckets. [1] For all of the data presented here the pre-trigger delay was set to zero turns.

The timing card was configured to perform the following operations:

- At the start of a cycle, wait for the BES.
- Watch passing AA markers, count down from the pre-trigger delay to zero.
- On the following 512 AA markers wait for the turn-by-turn delay and then issue an Echotek sync.

[1] The turn by turn delay is actually the sum of several components: a house delay, a per board delay and a per channel delay. In practice the board and channel delays were fixed at zero and we modified the turn by turn delay by modifying house delay.

- When 512 Echotek syncs have been issued, wait for the next BES.
- Repeat until the end of cycle TCLK event is received.
- Wait for the next master reset.

With this configuration the BPM will make two flash measurements per cycle, one for reach injection.

The integration window for the Echotek wide-band filter has been set to approximately 40 buckets, about half of the length of a batch. The raw data computed by Echotek are the complex numbers $A = (I_A, Q_A)$ and $B = (I_B, Q_B)$ that give the amplitude of the signals induced on the pickup. Two derived quantities are also computed, the sum signal, $(|A| + |B|)$, and the position, which was computed using the linear approximation,

$$P = -20.2 \frac{|A| - |B|}{|A| + |B|}, \tag{1}$$

where the position is given in mm.

2 The Two Datasets

2.1 Detailed Data

Most of the data shown in this note were obtained by logging into the front end computer and writing the flash buffers to disk. The disk files contain the full information, position, sum, (I_A, Q_A) and (I_B, Q_B) for all 512 turns in the flash. The typical sequence of operations was to set the house delay using the I43 program; enable data taking for a few seconds; disable data taking; write the buffers for flash 1 and flash 2 to disk; repeat. The reason for disabling data taking is to ensure that the two flash buffers written to disk are for the same instance of the MI cycle, not flash 1 from one instance of the cycle and flash 2 from the next.

The data collected this way was taken about 10:50 AM and 11:15 AM on Thursday Dec. 15, 2005.

Did Steve check for anomalously low cycles?

Figure 1 shows an example of typical sum and position data obtained this way. For the data in this figure, the house delay was set to 650 half-buckets, which centers the Echotek integration window on the batch.

From the figure we can see that the first beam arrived on turn 27 and that there are clear betatron and synchrotron motions in the position signal. In this figure one can see that the mean value of the sum signal, excluding turns with no beam, is about 3800 Echotek Units (EU).

2.2 The Data in Figure 2

The data shown in Figure 2 were collected differently. For this data set we were interested in only two numbers per delay: for both flash 1 and flash 2 we

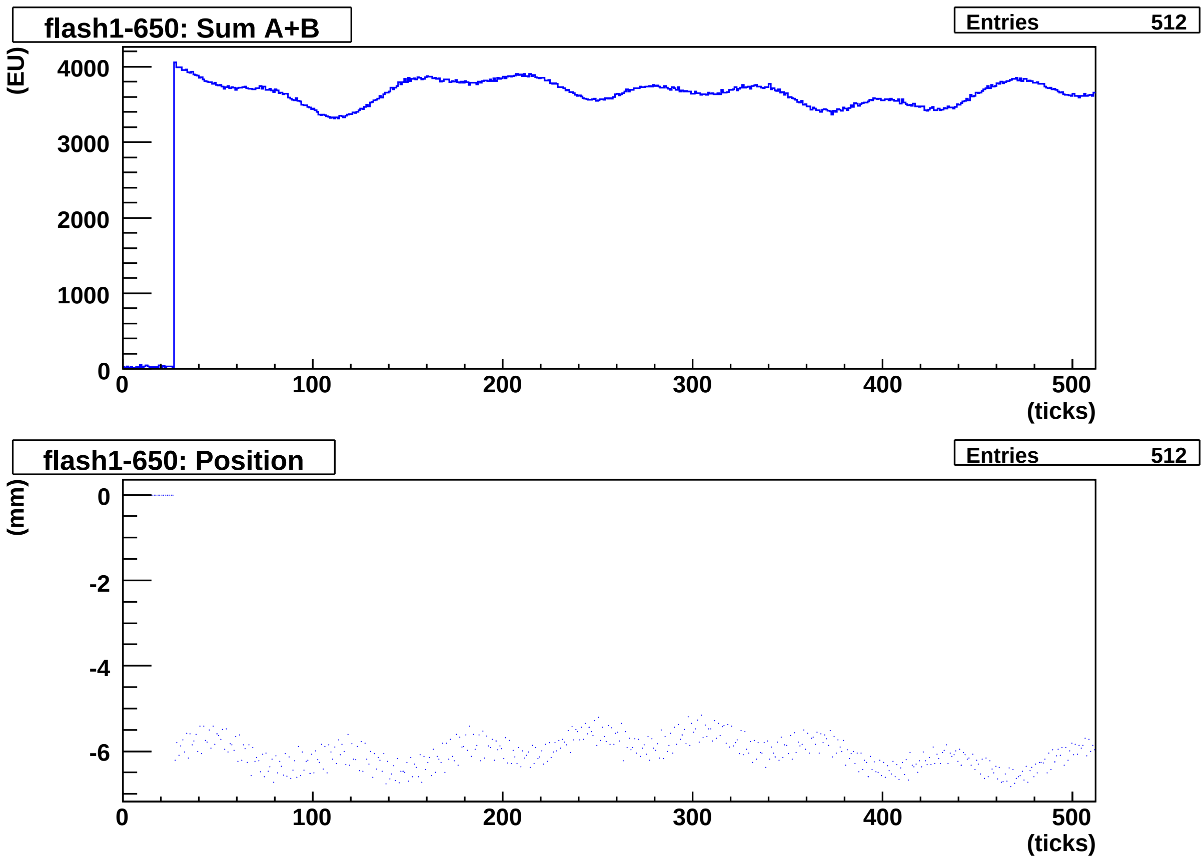

Figure 1: An example of a measurement from the first flash buffer. For this measurement the pre-trigger delay was set to zero and the house delay was set so that the Echotek gate was centered on the bunch. The upper plot shows the sum signal ($|A| + |B|$), with the vertical scale in Echotek Units (EU), while the lower plot shows the linear approximation to the position. The first two data points in this dataset contained uninitialized data and were arbitrarily set to zero.

recorded the average value of the sum signal over all 512 turns, excluding turns with no beam present. This measurement was made by looking at the intensity plot presented by I43 and reading the values by eye. When looking at data this way, one sees that most instances of the cycle have the same sum signal to about 5%. There are, however, occasional instances of the cycle with an anomalously low sum signal. Each data point reported here was obtained by watching several repeats of the cycle in order to exclude the anomalously low cases.

The data collected this way were taken in a 10 minute period at about 11 AM on Wednesday Dec. 14, 2005.

2.3 Comparing the Two Datasets

While the information within each dataset is self consistent, one should be careful about quantitative comparisons between the data sets. Both datasets contain, for example, information about flash 1 for a house delay of 650 half-buckets. In the detailed dataset the mean value sum signal is reported as 3800 Echotek Units (EU) while in Figure 2 the same number is reported as 3000 EU. This simply reflects a change in beam intensity between over the day between these two studies.

Check that trends do indeed follow.

3 Scanning the House Delay

The upper plot in Figure 2 shows how the mean sum signal varies as the house delay is scanned from 500 to 800 half-buckets. Details of how these data were taken are given in section 2.2. The data points in the figure are also presented in Table 1.

The observed sum signal will drop to half of its maximum value when the integration window is centered on the edge of the batch. The red horizontal dashed line is drawn at half of the maximum value and the red vertical dotted lines were placed, by eye, where the red horizontal dashed line intersects the blue line connecting the data points. These vertical dotted lines delimit the edge of the batch and are drawn at 572 half-buckets and 731 half-buckets, a difference of 79.5 buckets. This agrees with the expected batch length of 80 buckets.

The upper plot in Figure 2 is shown in the raw units of half-buckets and EU. The second plot shows the same data transformed into more useful units; the horizontal axis was changed to buckets and the vertical axis was changed to "bunches", as follows. The integration window of the Echotek is approximately 40 buckets (753 ns). Assuming that, within a batch, all buckets are filled with identical bunches, the peak measured value should be 40 bunches; therefore the data were scaled linearly so that the middle point has a value of 40. The predicted response for 80 identical bunches with an integration window of 40 bunches is shown as the superimposed magenta line. As a cross check, the rising and falling slopes were measured using the two pairs of points shown in red. The

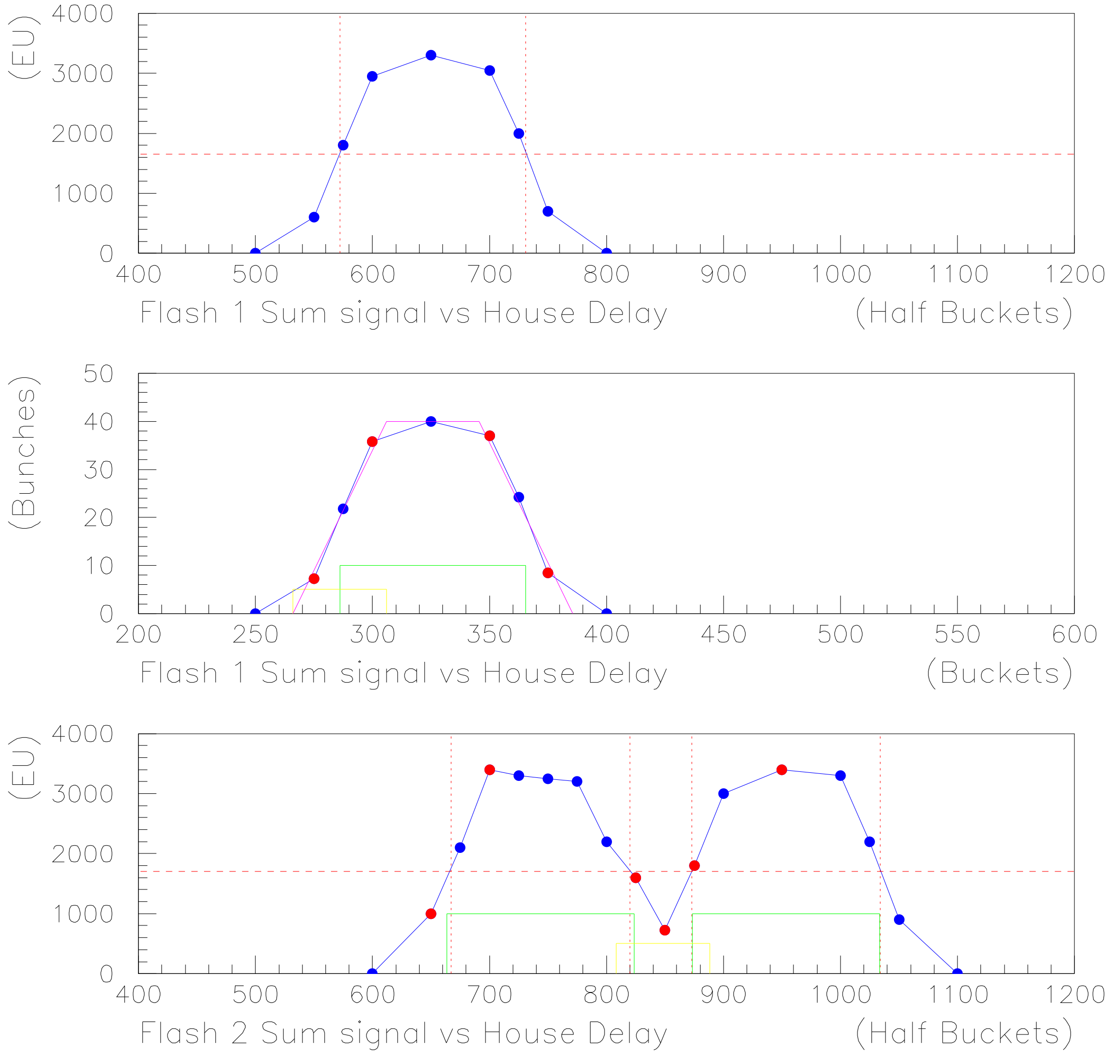

Figure 2: The upper plot shows how the average of the sum signal from the first flash depends on the house delay. The horizontal axis is in half-buckets and the vertical axis is in Echotek Units (EU). The second figure shows the same data with the axes transformed to buckets and batches, as described in the text. The bottom plot shows how the average of the sum signal from the second flash depends on the house delay. The overlayed lines on all figures are described in the text. For the points drawn in red, detailed plots are shown in the following figures.

	Flash 1		Flash 2	
	House Delay (Half-Buckets)	Sum (EU)	House Delay (Half-Buckets)	Sum (EU)
1	500	0	600	0
2	550	600	650	1000
3	575	1800	675	2100
4	600	2940	700	3400
5	650	3300	725	3300
6	700	3050	750	3250
7	725	2000	775	3200
8	750	700	800	2200
9	800	0	825	1600
10			850	725
11			875	1800
12			900	3000
13			950	3400
14			1000	3300
15			1025	2200
16			1050	900
17			1100	0

Table 1: Raw data from the scan of the house delay. These data are displayed in Figure 2.

rising slope is $+1.14 \pm 0.08$ and the falling slope is -1.14 ± 0.08 (yes the values are the same!). The errors are $1\,\sigma$ errors and were computed assuming a 5% error in the value of the sum signal at each point. These slopes are consistent with the expected value of ± 1.0 bunches per bucket. This simple model is a very good description of the data.

For completeness, we can solve for scale factor that gives slopes of ± 1.0 bunches/bucket. This gives a peak sum signal of 35.1 bunches with a $1\,\sigma$ error of a few bunches.

The green and yellow boxes are included as cartoons to guide the eye. The green box shows the extent in time of the batch and the yellow box shows the extent in time of the integration window, centered on one edge of the batch. The cartoon is a little misleading because the horizontal axis is actually the time delay to the start of the Echotek window, but the points track the location of the center of the Echotek window. This is not important unless one wants to compare to an external time reference.

The bottom plot in Figure 2 shows the average sum signal in the second flash buffer as a function of the house delay. The same house delay is applied to both flashes. In this figure one can see both batches. Section 5 will show that show that the batch extending from about 663 to 823 half-buckets is the batch already in the machine, while the batch extends from about 873 to 1033 half-buckets is the newly injected batch. The red dashed and dotted lines are the construction lines to guide the eye finding the batch edges; they were constructed the same way as the corresponding lines in the top figure on this page. From each pair of dotted lines one can estimate the position of the batch center.

The green and yellow boxes are included as cartoons to guide the eye. The green boxes represent the positions of each batch; they are drawn 80 buckets wide, centered on the estimated batch center. The yellow box shows the length of the integration gate, 40 bunches, centered on the gap between the batches.

In this picture, the gap between buckets is about 5/8 of the integration window. The following discussion will assumes that all 160 bunches in the machines are identical. For the data point at a house delay of 850 half-buckets, the Echotek window is approximately centered on the gap between the batches. So one would naively predict that the sum signal would be 3/8 of the maximum sum signal, or about 1240 EU. The data point is well below this value. This will be discussed in section 5.

4 Detailed Plots

Figures 3 through 10 show the full turn by turn information for both flashes for six selected house delays; the six plots on each page show one quantity for each of the six delays. Figure 3, for example, shows the sum signal for the full 512 turns of flash 1 for the six different house delays. The title of each histogram, at the upper left of the histogram, contains the following information,

- "flash1-" or "flash2-", which indicates from which flash buffer the data was taken.

- A three digit number, 650, 700, 825, 850, 875 or 950, which indicates the delay, in half-buckets.
- The quantity that is plotted, one of:
  - the sum signal.
  - the position.
  - the magnitude of the Fourier transform of the sum signal.
  - the magnitude of the Fourier transform of the position.
  - the phase of the complex number A, $\arg(A)$.
  - the phase difference between A and B, $\arg(A) - \arg(B)$.

If the sum signal is less than 100 EU, then all other quantities for that data point are set to zero; the sum signal itself is not zeroed.

When the Fourier transforms are computed, only data with a sum signal above 100 EU is used and the mean value of the data is subtracted before computing the transform. The transforms are always displayed using the same number of bins as there are data points that survive the cut on the sum signal; that is, if there are 483 turns with beam above threshold, then the transforms will also have 483 bins.

5 Discussion

5.1 Which Batch is Which?

The information in Figures 3 and 5 can be used to untangle which batch is which in the bottom plot in Figure 2. In Figure 3, the upper two plots provide a reference to show what an injection looks like when it is uncontaminated by a neighboring batch: there are 27 or 28 turns with no beam, followed by a jump to the full intensity for that delay. The bottom two plots Figure 5 show the same behavior. So these plots must be measuring the second batch injected into the machine. A particularly interesting plot is the middle right, which was made with a delay of 850 half-buckets. This plot shows a small but non-zero sum signal for 28 turns and then a jump to a higher sum signal on the next turn. To get this behavior the Echotek window must include the tail end of the first batch, the front end of the second batch and empty buckets in between. For the first 28 turns the second batch is not in the machine and most of the Echotek window contains no beam, giving the small sum signal. On the next turn, the second batch has been injected and part of that batch is included in the Echotek window, giving a jump in the sum signal. This is the situation depicted by the green and yellow cartoon boxes in the bottom plot in Figure 2. The large oscillations will be explained later.

The other three plots on the page show a non-zero signal in all bins with no abrupt jumps. This is the expected behavior if the Echotek window contains only bunches from the first batch. All six of the plots on this page are consistent with the batch timing inferred from the bottom plot in Figure 2.

5.2 Explaining the Slopes in Figure 5

The first three plots in Figure 5 have another prominent feature: they show a steady slope with a small modulation, the first two plots having a rising slope and the third a falling slope. Both will now be explained.

The slope can be explained with the aid of Figure 11. All four plots in that figure shows a cartoon of a slice of time with three Echotek windows represented by the red, green and yellow boxes. These boxes correspond to the Echotek windows used to make the first three plots in Figure 5. In this point of view, time is fixed to the RF signal coming into the timing card, which is synced to the frequency of the central orbit. The first batch, on the other hand, is at a smaller radius than the central orbit and on different turns will appear at slightly different times. The top plot shows the position of the first batch on the first turn measured in the second flash. The batch intersects only a small part of the the red window, which corresponds to a house delay of 650 half-buckets. On the other hand, the batch intersects almost all of the green window, which corresponds to a house delay of 700 half-buckets. So one would expect that, on the first turn, the sum signal for a delay of 700 half-buckets should be much larger than that for a delay of 650 half-buckets. This is indeed observed in the top two plots of Figure 5. On subsequent turns, the beam arrives at later and later times, as represented in the other three plots in Figure 11. On these subsequent turns, the batch slides out of both the red and green windows, and the one would expect that the sum signal for these delays would show a downward slope. This is indeed observed.

The picture for the yellow window, which represents the Echotek window for a house delay of 825 half-buckets, is a little different. On the first turn the batch intersects only a part of the yellow window so the sum signal starts out small. As time increases, however, the batch moves more and more into the yellow window; therefore the sum signal for a delay of 825 half-buckets should increase with time. This is also observed.

The cartoon correctly explains the slopes but it does not correctly explain the relative size of the initial signal for house delays of 650 and 825 half-buckets. This could be explained by bunches being non-uniform within the batch or by the Echotek windows being a little longer than 40 bunches.

5.3 Explaining the Modulation in Figure 5 - Part I

The modulation present on the first three plots of Figure 5 is also easy to explain. If we presume that the Echotek window is not an integer number of buckets in length, then the Echotek output will be modulated by the variation of which part of the fractional bucket is inside the gate. Recall that the Echotek samples the output of the ringing filter and does not see the bunch directly. So the observed modulation comes from sampling different parts of the filter output.

This picture can be reinforced by looking at the first three plots in Figure 8. These plots show how the phase of A depends on the turn number. The physical meaning of the phase of A is the arrival time, at the Echotek board, of the signal

Turn #	Δ(Turn #)
38	
100	62
164	64
230	66
296	66
360	64
423	63
487	64

Table 2: The left column gives the turn number at which the minima occur in the upper left plot in Figure 8. The right column gives the difference between this minimum and the previous one. The average difference is 64.3 turns and there is a greater variation than that caused by the granularity of the sampling period.

from the first batch relative to the start time of the Echotek. As the batch slips by one bunch relative to the central orbit, the phase of A rotates through 2π. This phase rotation is clear in the first three plots in Figure 8 and it has the same periodicity as the modulation in the first three plots in Figure 5, a shift of one bunch every 64.3 turns. Table 2 lists the positions of the minima in the upper left plot in Figure 8. If the rate of slipping were exactly uniform one would expect to only see Δ values of 64 or 65, never 62 or 66. Therefore the rate of slipping does have small but measurable variations.

5.4 Explaining the Modulation in Figure5 - Part II

The modulation in the plot for a house delay of 850 half-buckets has a different source. For the first 28 turns, the second batch is not yet in the machine and only the first batch contributes to the measurement. After 28 turns, the second batch is in the machine and the measurement contains contributions from both batches. A cartoon of this situation is drawn on the bottom plot of Figure 2. The following model describes the gross features of this situation.

Let the complex number a denote the full measurement. It contains two contributions, a_1 from the first batch and a_2 from the second batch,

$$a = a_1 + a_2. \tag{2}$$

In this model the second batch does not slip wrt the timing of the central orbit. So the magnitude of a_2 is a step function that turns on at turn 28 and and phase of a_2 is a constant, chosen to match the data,

$$|a_2| = \left\{ \begin{array}{cc} 0 & t < 28 \\ a_{20} & t \geq 28 \end{array} \right\} \tag{3}$$

$$\phi_2 = \phi_{20} \tag{4}$$

Batch one, on the other hand, does slip wrt to the timing of the central orbit. Let t denote the turn number and m denote the rate, measured in fractions of a bucket per turn, at which the first batch slips. Using the results of the previous section $m = 1/64.3$. Both the the magnitude and phase of of a_1 increases linearly with turn number:

$$
\begin{aligned}
|a_1| &= a_{10} + \delta_a m t && (5)\\
\phi_1 &= \phi_{10} + 2\pi m t && (6)\\
& && (7)
\end{aligned}
$$

where a_{10}, δ_a and ϕ_{10} are constants. The blue lines in Figure 12 show the sum signal and the phase of A from flash 2 with a house delay of 850 half-buckets; these are the same data shown in Figures 5 and 8. The results of the model are superimposed on the data. The parameters of the model were fiddled, by eye, to get the a reasonable match to the data; the values are $a_{10} = 275$, $\phi_{10} = -0.40$, $\delta_a = 48$, $a_{20} = 550$ and $\phi_{20} = 1.65$. A quick glance at the plot suggests that I should reduce δ_a but that removes the agreement with the phase data.

The model correctly describes the gross features of the sum signal when both batches are present: the growing oscillation. It does not quantitatively describe the growth rate of the oscillations. It also qualitatively describes the main features of the phase of A after turn 28: the sawtooth shape of the modulation and the sudden jumps near turns 400 and 460. But it gets the sign wrong for one of the jumps. If I reduce δ_a to 45, then the sudden jumps in the phase go away and the pattern from earlier turns continues. I don't understand why the phase in the measured data is so stable for turns 0 to 28.

The model excludes synchrotron motion and quadrupole oscillations. The former is somewhat cancelled out because I am comparing the model to the sum signal, not to the data for A or B; but the cancellation is not perfect. Also, inspection of Figure 17 shows that batch 2 has strong quadrupole oscillations.

I had expected δ_a to be closer to 100.

5.5 Check Timing Relative to I6

The I6 program tells us that, for state 28, the first bunch in the first batch is targeted for bucket 466 and that the first bunch in the second batch is targeted for bucket 28, both relative to the AA marker. Because of cable length differences and so on we do not expect these absolute numbers to be present in our data. However we do expect the difference to be preserved; relative to the preceeding AA marker, the second batch should arrive 438 buckets before the first did.

In the setup at MI40, the house delay is measured relative to the first AA marker that follows the arrival of the BES at the timing card. In the discussion of the top plot in Figure 2, it was stated that the first bunch of the first batch arrived at a delay of 572 half-buckets. In the discussion of the bottom plot in Figure 2, it was stated that the first bunch of the second batch arrived at a delay of 873 half buckets, a difference of 150.5 buckets. Oddly the second bunch is arriving at a later time than the first, not an earlier time. Presumably this is just confusion counting turn numbers correctly.[2] If we have miscounted turns by one, then the predicted arrival time of the second batch, relative to the first batch, changes from -438 buckets to +150 buckets. This agrees with the measured value.

6 Known Bugs and Work List

- What is the gate length? Is it really fractional? Can I Make the discussion of the last figure quantitative?
- Two low points in fig 7.
- Upper left plot in Figure 10. Why does this oscillation develop?

7 Summary

I have shown the results of my first attempts to look at beam with the test MI BPM system. Some things look good but there are a number of anomalies. One anomaly is that raw IQ values coarsely quantized, which should be fixed. I can't yet explain the other anomalies. I will look into them but I welcome any ideas that others have.

[2]On several occasions we have noticed that there is a +/1 turn jitter in the turn at which the first bunch arrives.

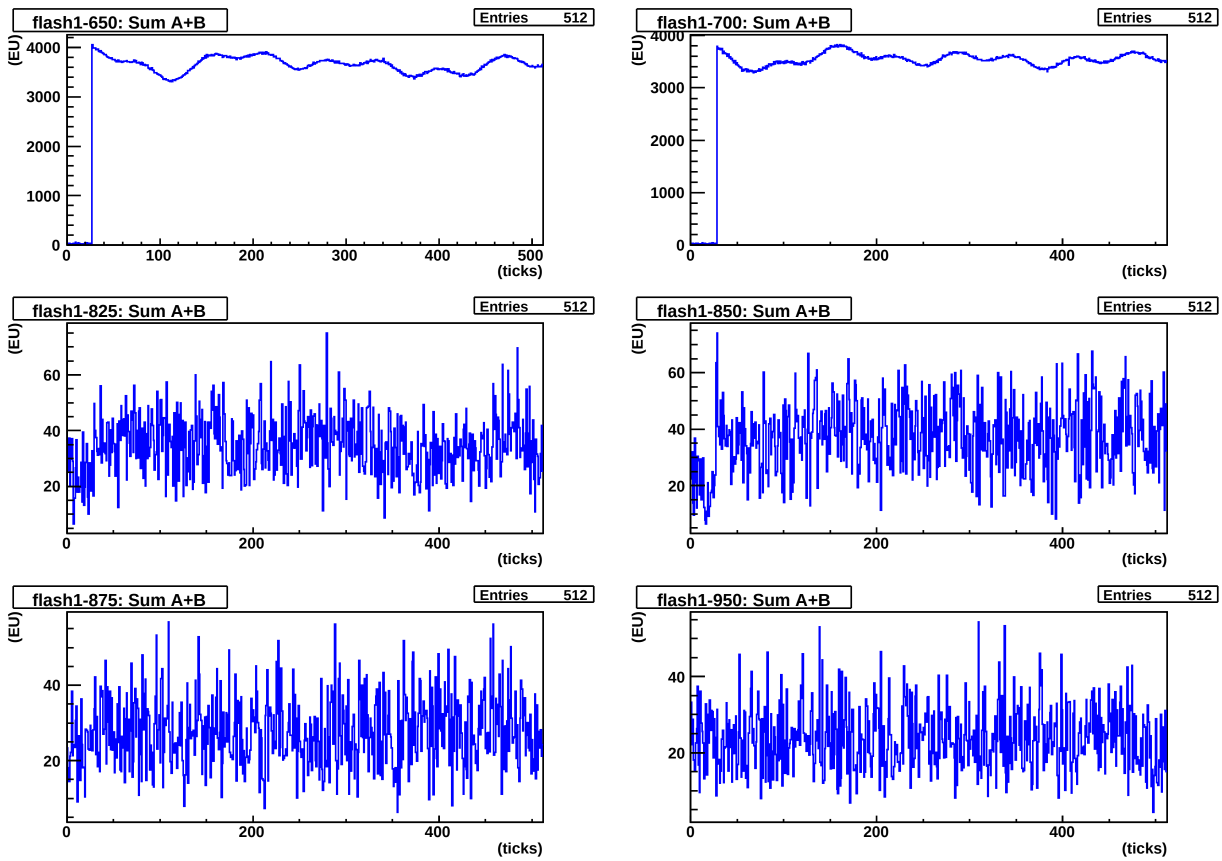

Figure 3: The sum signal for flash 1 for the six different house delays; the delay is encoded in the histogram title.

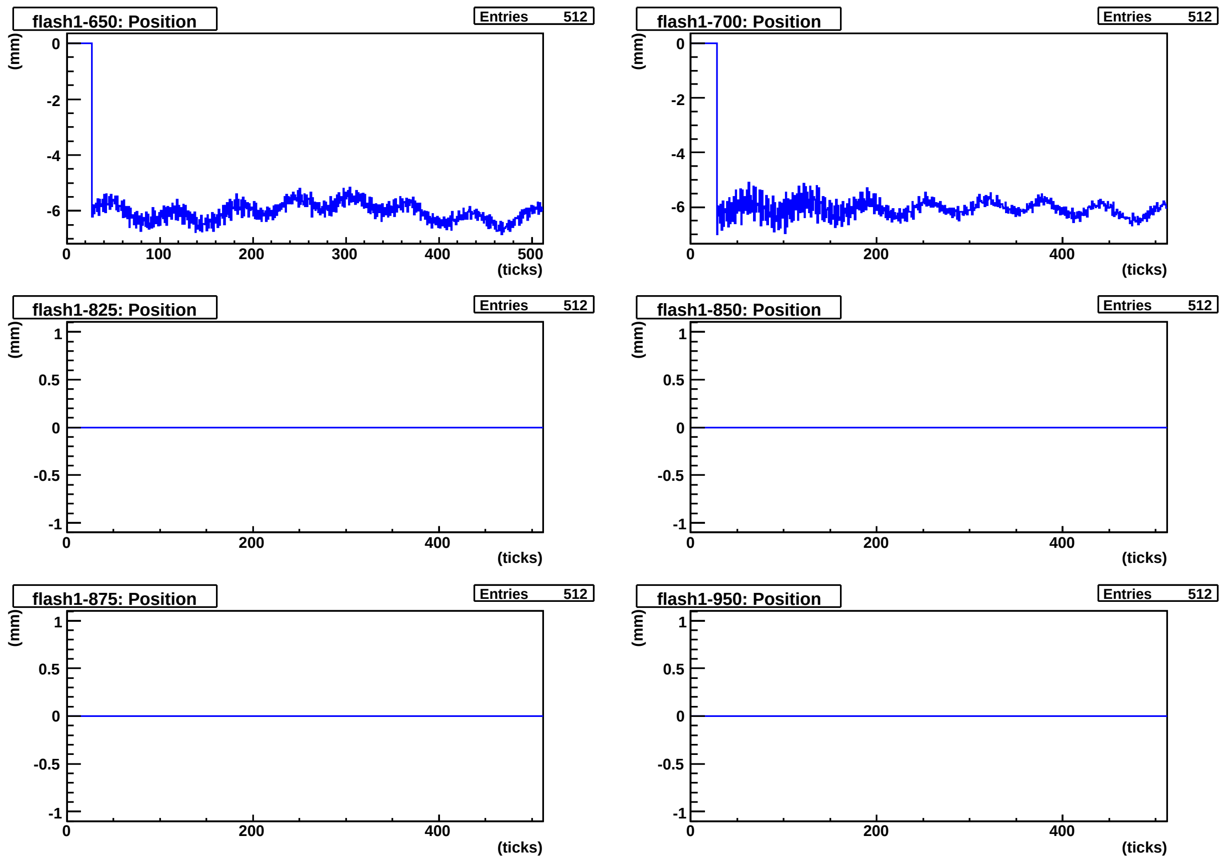

Figure 4: The position for flash 1 for the six different house delays; the delay is encoded in the histogram title. When the sum signal is less than 100 EU the position is set to zero.

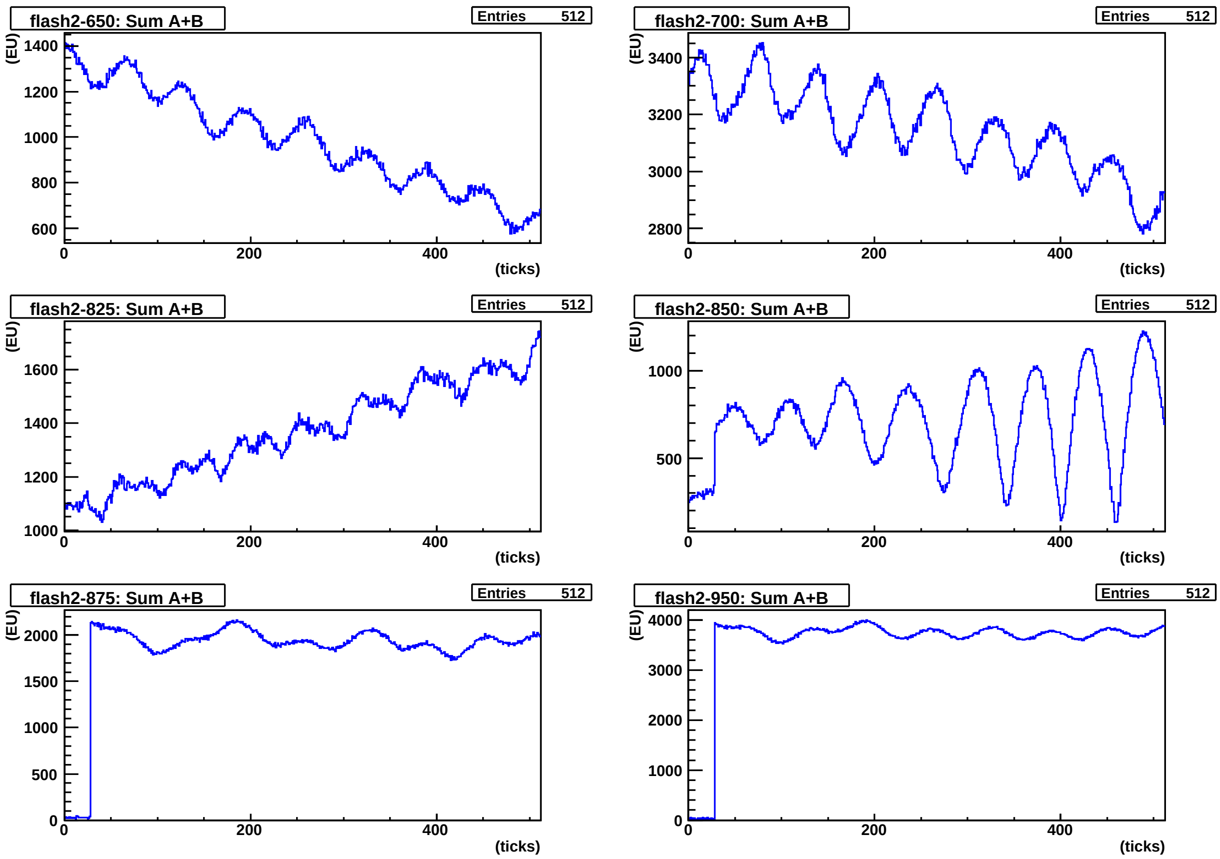

Figure 5: The sum signal for flash 2 for the six different house delays; the delay is encoded in the histogram title. The structure in these plots is discussed in the text.

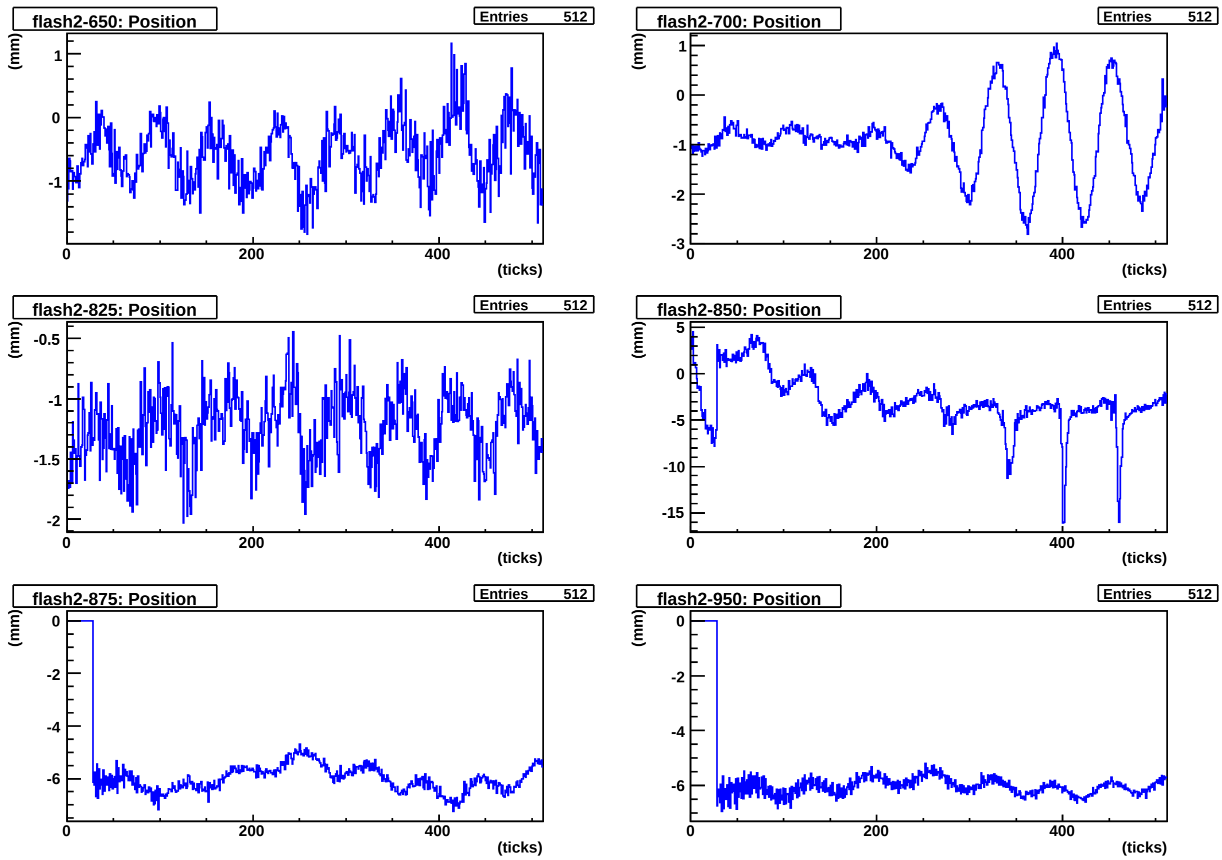

Figure 6: The position for flash 2 for the six different house delays; the delay is encoded in the histogram title. When the sum signal is less than 100 EU the position is set to zero.

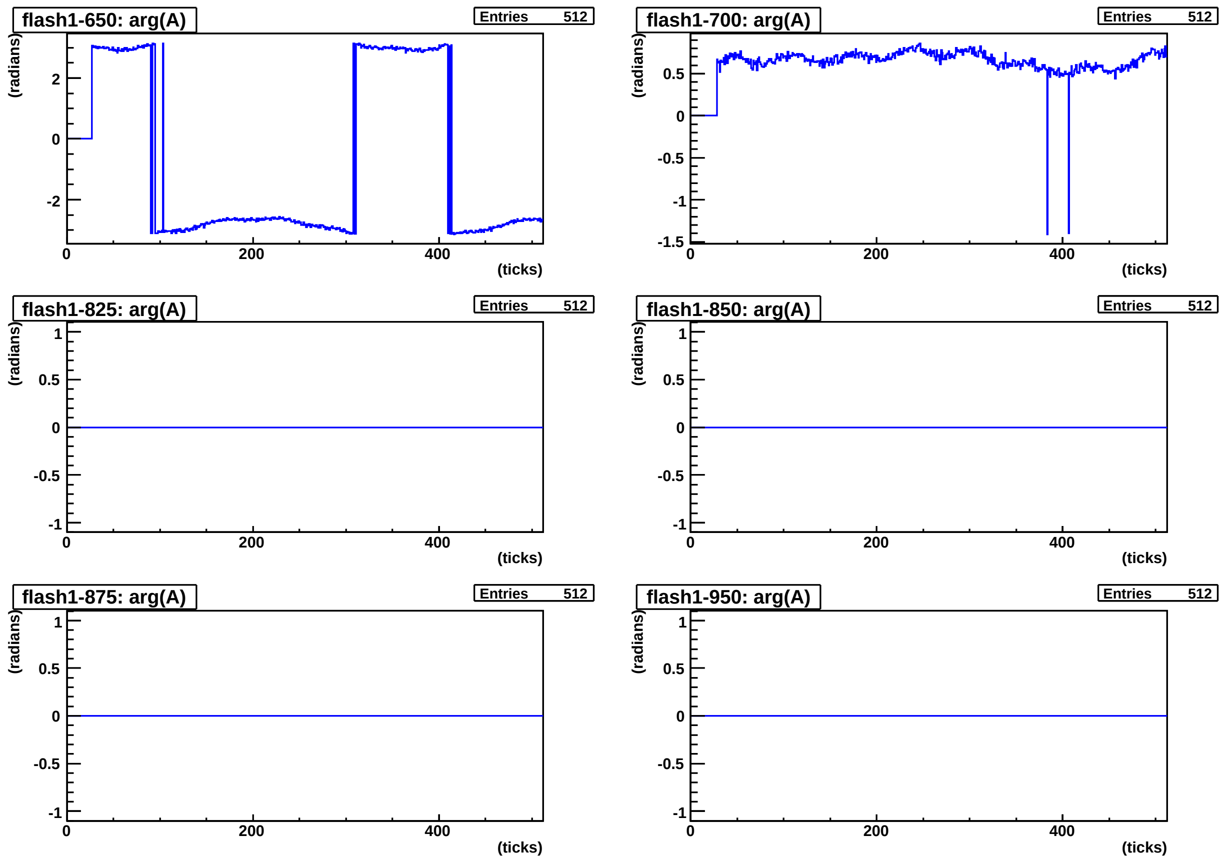

Figure 7: The phase of the complex number A from flash 1 for the six different house delays; the delay is encoded in the histogram title. For points with a sum signal of less than 100 EU, the phase was set to zero. The jumps in the data in the upper left plot are artifacts of displaying the phase on the range $[-\pi, \pi]$; the data would be smooth if it were shown on $[0, 2\pi]$. The two low points in the upper right plot are unexplained.

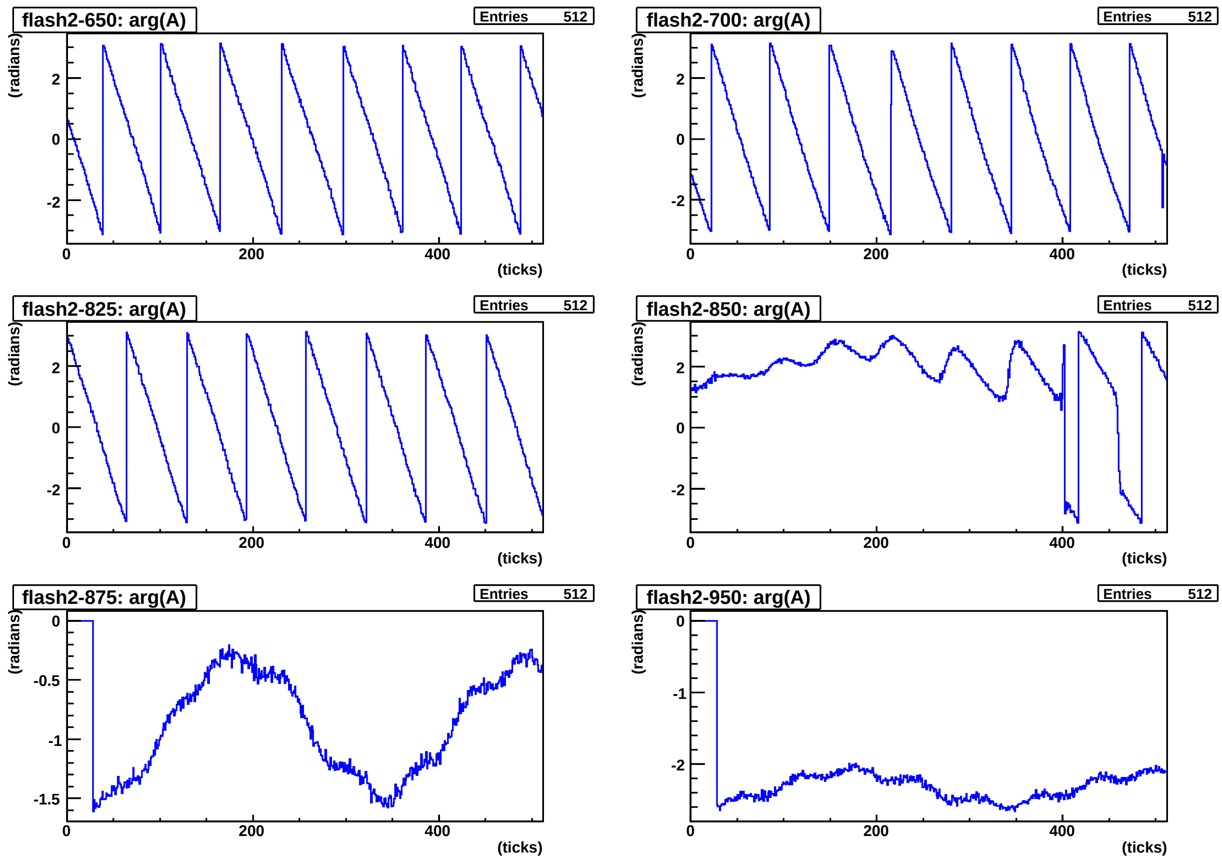

Figure 8: The phase of the complex number A from flash 2 for the six different house delays; the delay is encoded in the histogram title. For points with a sum signal of less than 100 EU, the phase was set to zero. The structure in these plots is discussed in the text.

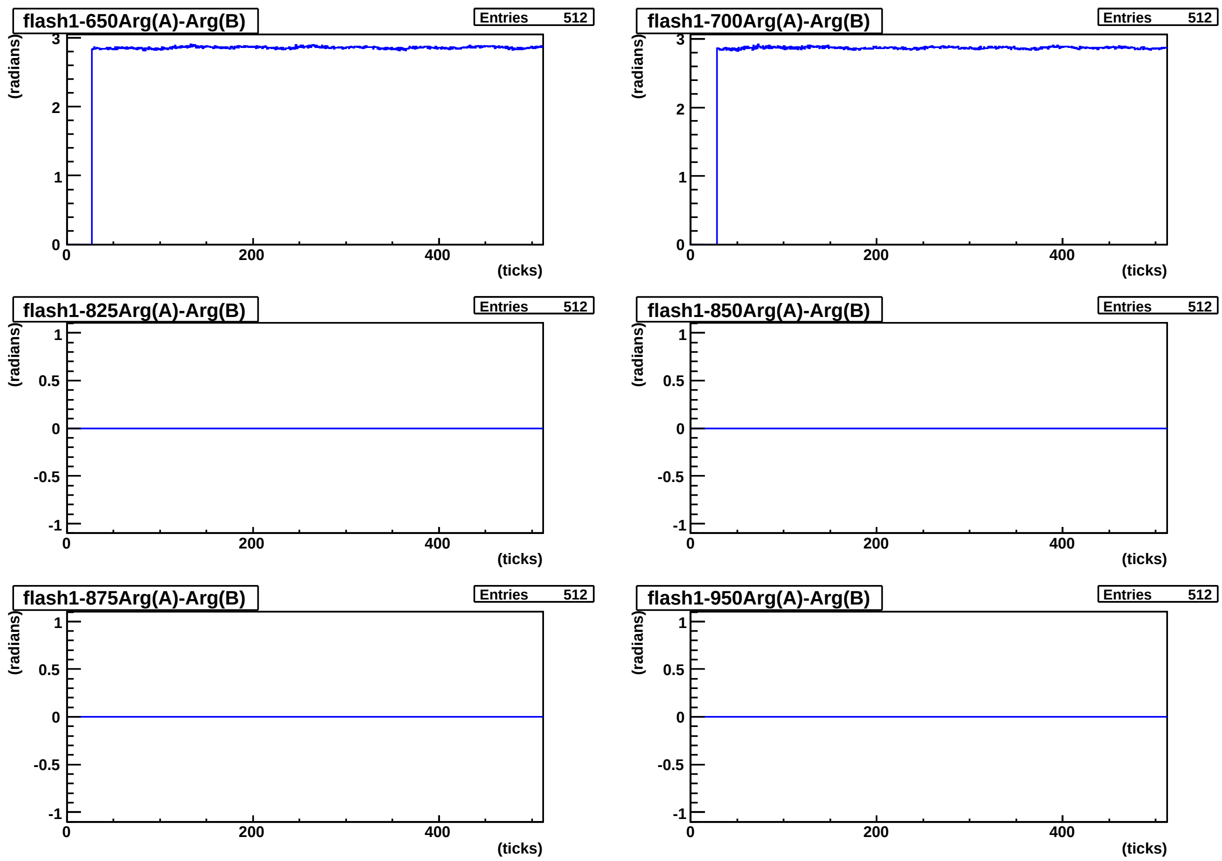

Figure 9: The phase difference between the complex numbers A and B from flash 1 for the six different house delays; the delay is encoded in the histogram title. For points with a sum signal of less than 100 EU, the phase difference was set to zero.

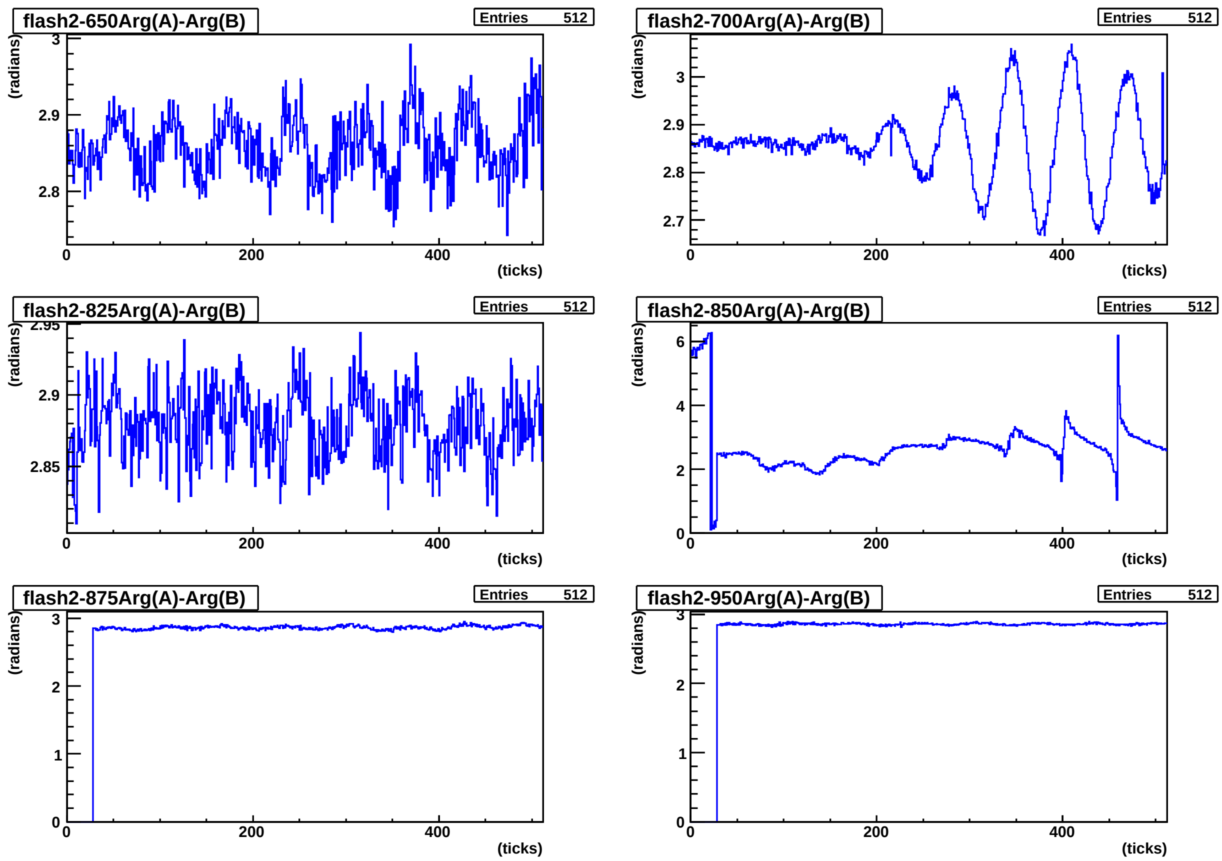

Figure 10: The phase difference between the complex numbers A and B from flash 2 for the six different house delays; the delay is encoded in the histogram title. For points with a sum signal of less than 100 EU, the phase difference was set to zero.

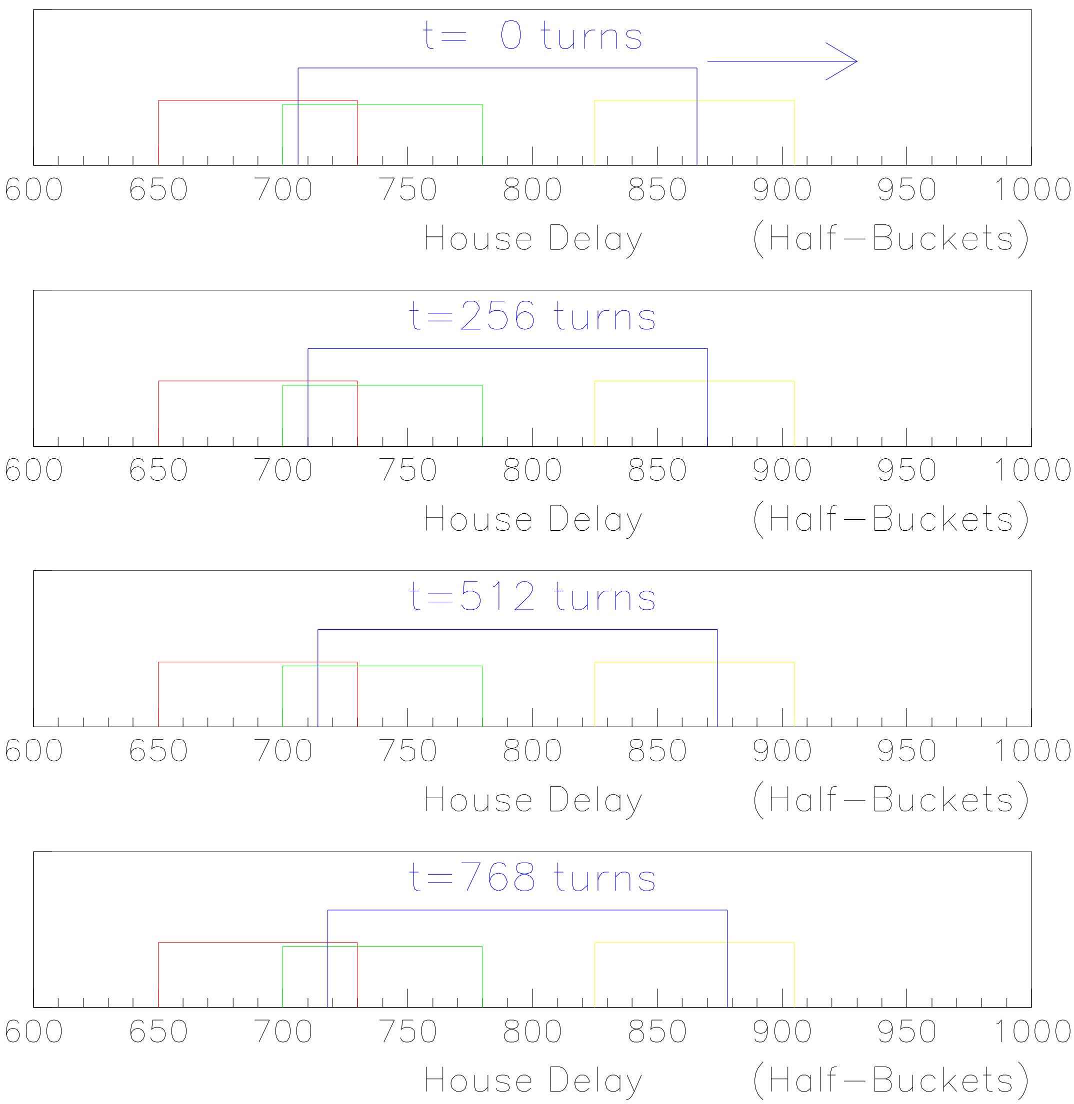

Figure 11: Cartoon of slipping. In all 4 plots the horizonal axis is house delay in half-buckets and the vertical axis is arbitrary units. All 4 plots have identical red, green and yellow boxes drawn on them; these represent the Echotek windows corresponding to house delays of 650, 700 and 825 half-buckets. On each plot the blue box represents the position of the batch at the specified turn.

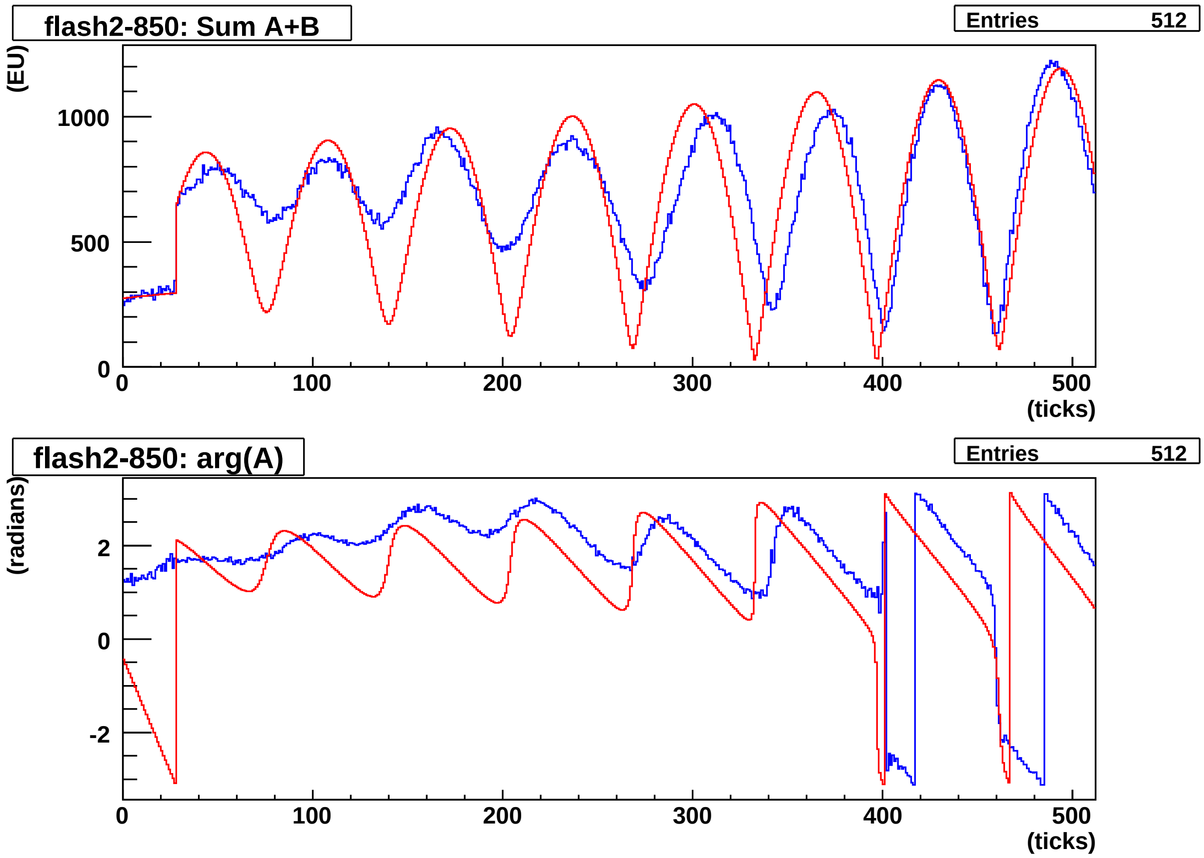

Figure 12: The blue lines copies of the data for a delay of 850 half-buckets taken from Figures 5 and 8. The red lines the output of a model that is intended to describe the main structures in the data. The model is described in the text.

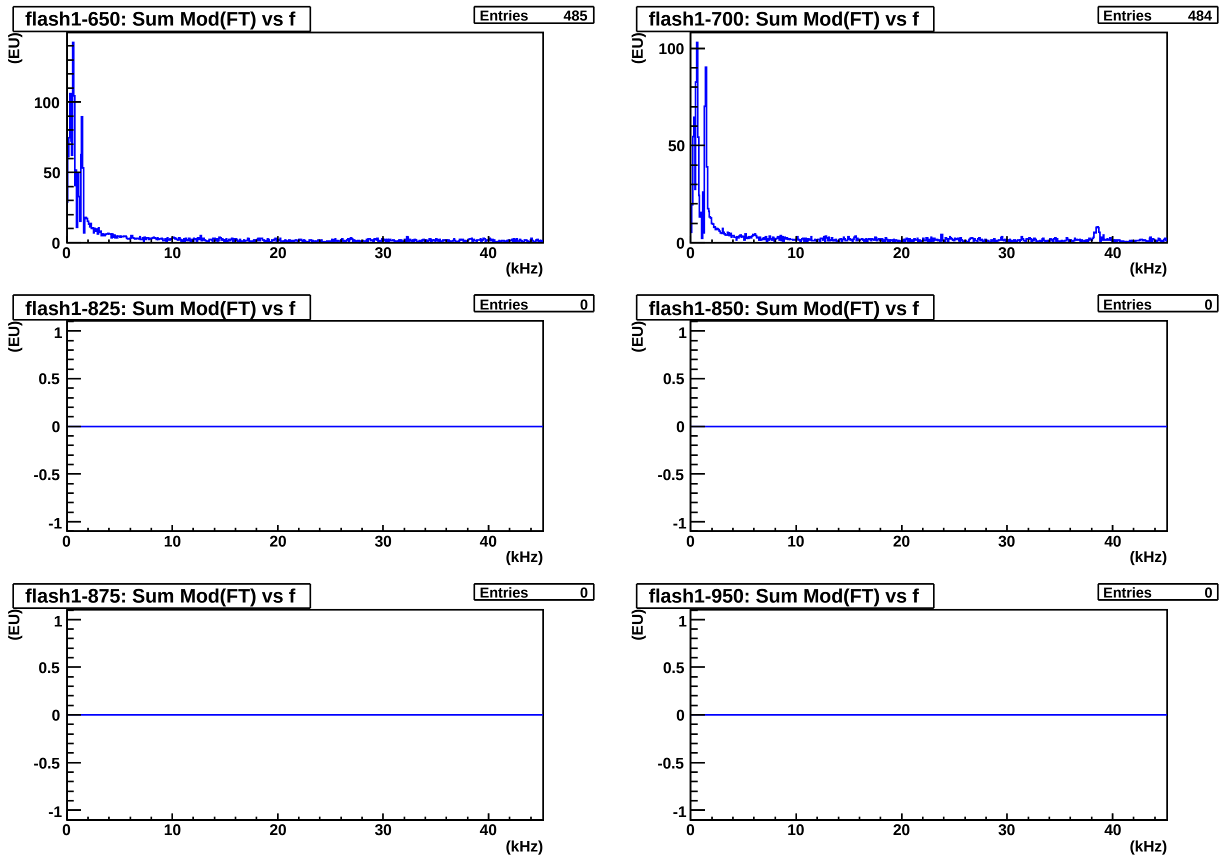

Figure 13: The magnitude of the Fourier transform of the sum signal for flash 1 for the six different house delays; the delay is encoded in the histogram title. Only points with a sum signal above 100 EU were included in the transform. The mean value of the sum signal was subtracted before computing the Fourier transform.

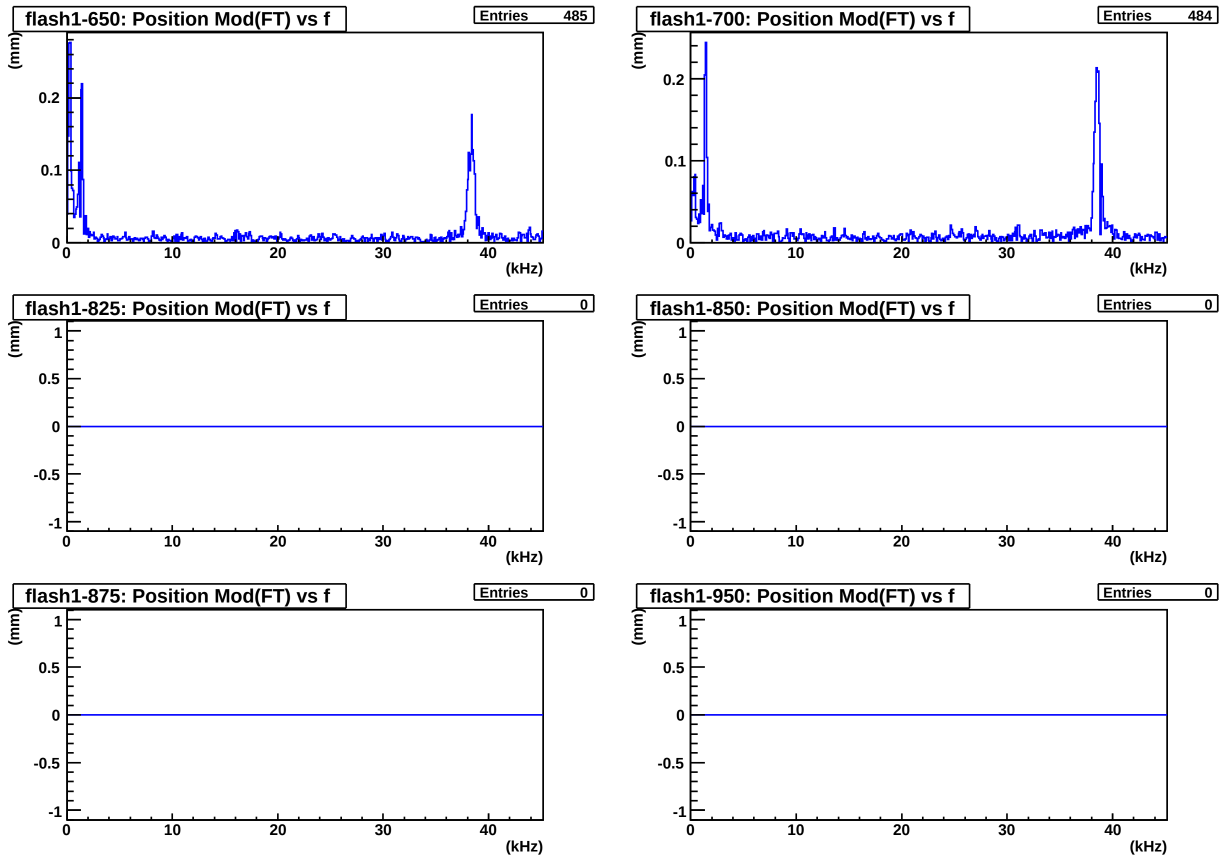

Figure 14: The magnitude of the Fourier transform of the position for flash 1 for the six different house delays; the delay is encoded in the histogram title. Only points with a sum signal above 100 EU were included in the transform. The mean value of the position signal was subtracted before computing the Fourier transform.

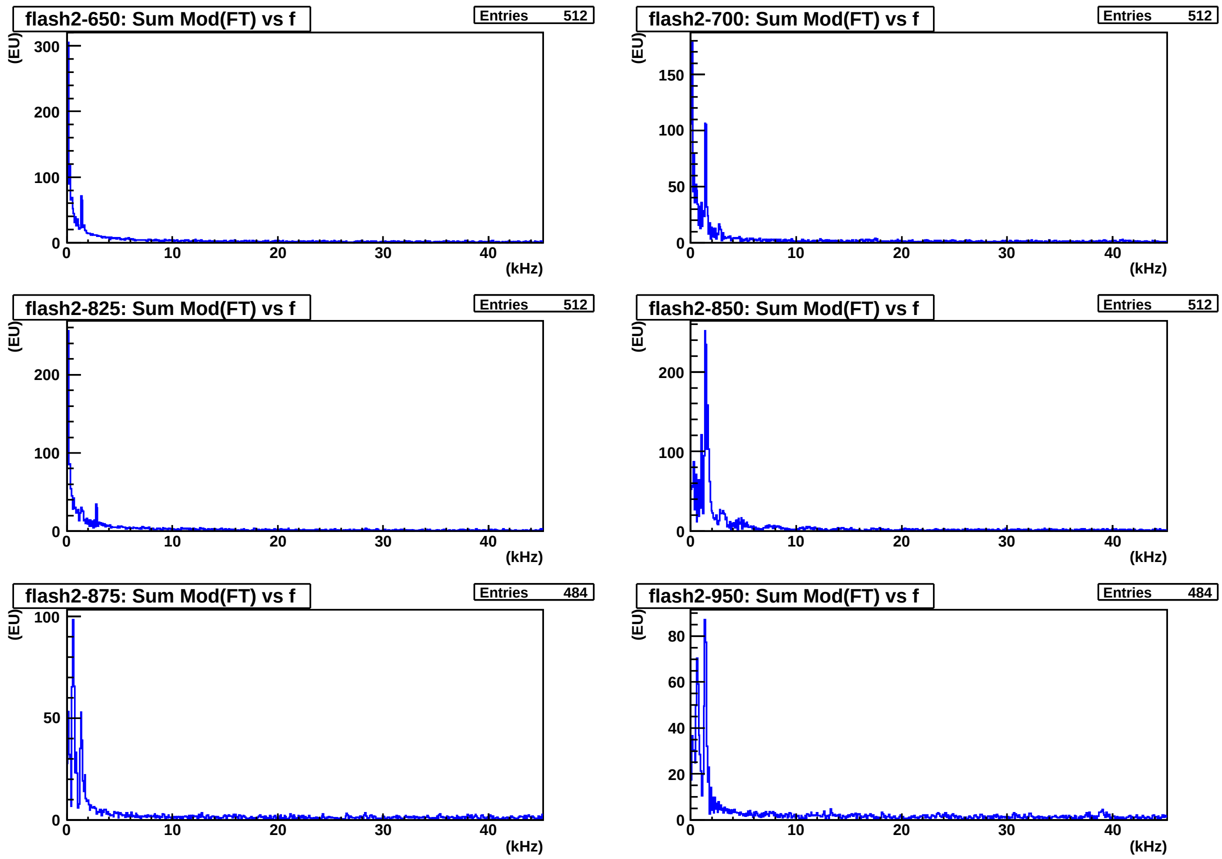

Figure 15: The magnitude of the Fourier transform of the sum signal for flash 2 for the six different house delays; the delay is encoded in the histogram title. Only points with a sum signal above 100 EU were included in the transform. The mean value of the sum signal was subtracted before computing the Fourier transform.

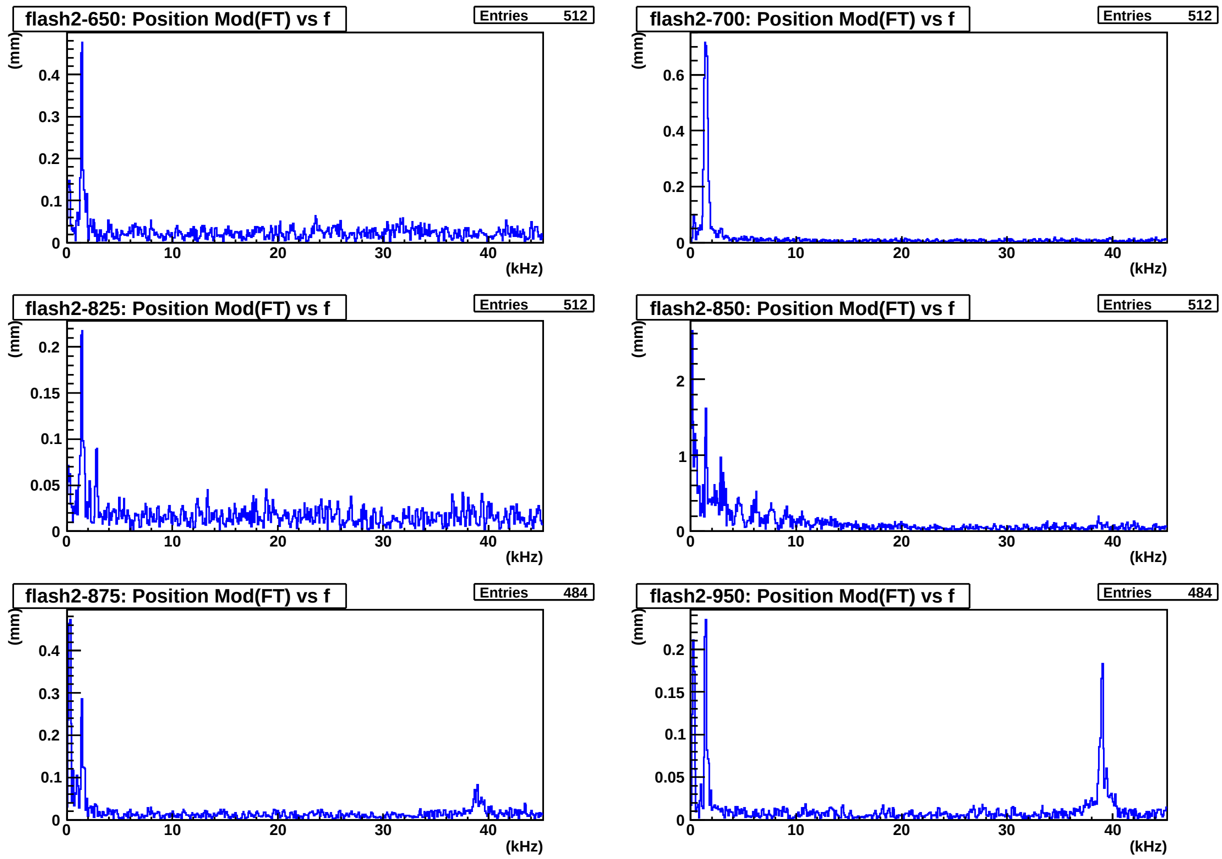

Figure 16: The magnitude of the Fourier transform of the position for flash 2 for the six different house delays; the delay is encoded in the histogram title. Only points with a sum signal above 100 EU were included in the transform. The mean value of the position signal was subtracted before computing the Fourier transform.

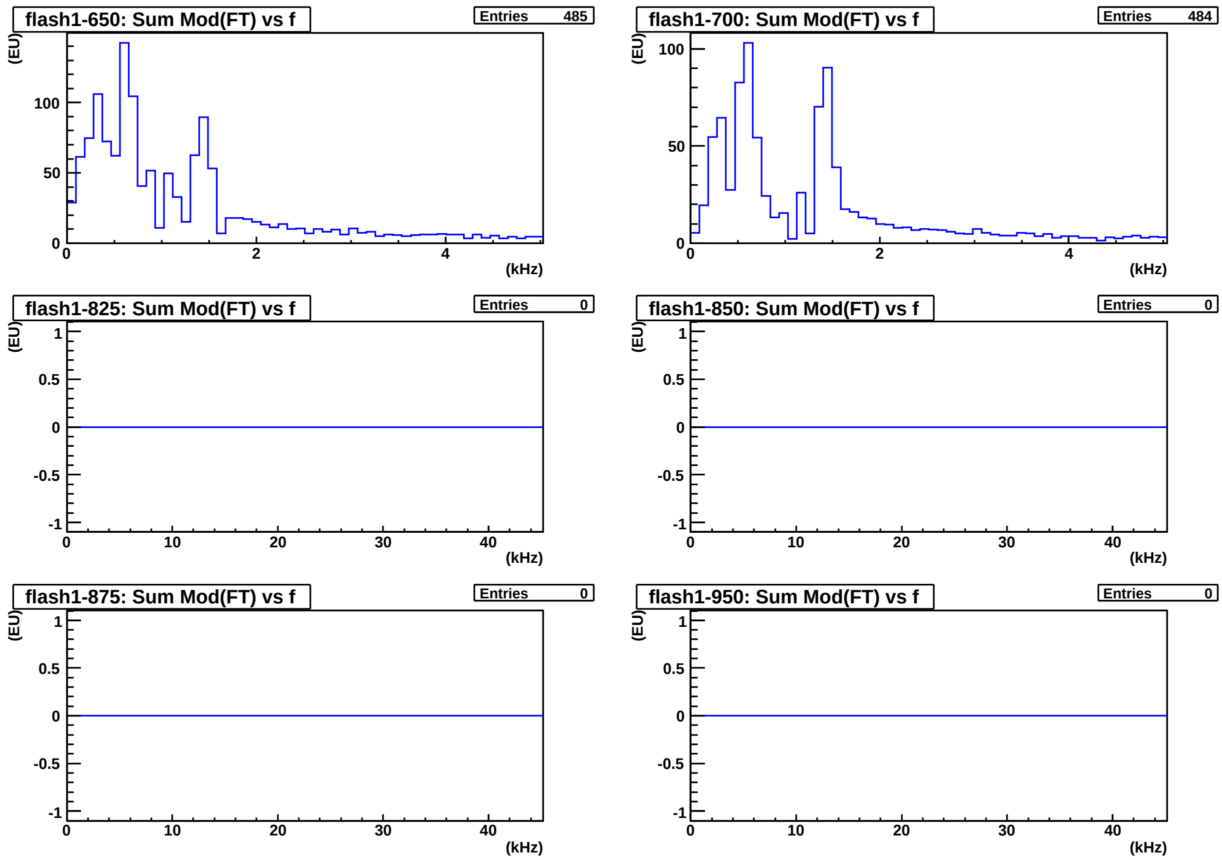

Figure 17: Detail of Figure 13. The magnitude of the Fourier transform of the sum signal for flash 1 for the six different house delays; the delay is encoded in the histogram title. Only points with a sum signal above 100 EU were included in the transform. The mean value of the sum signal was subtracted before computing the Fourier transform.

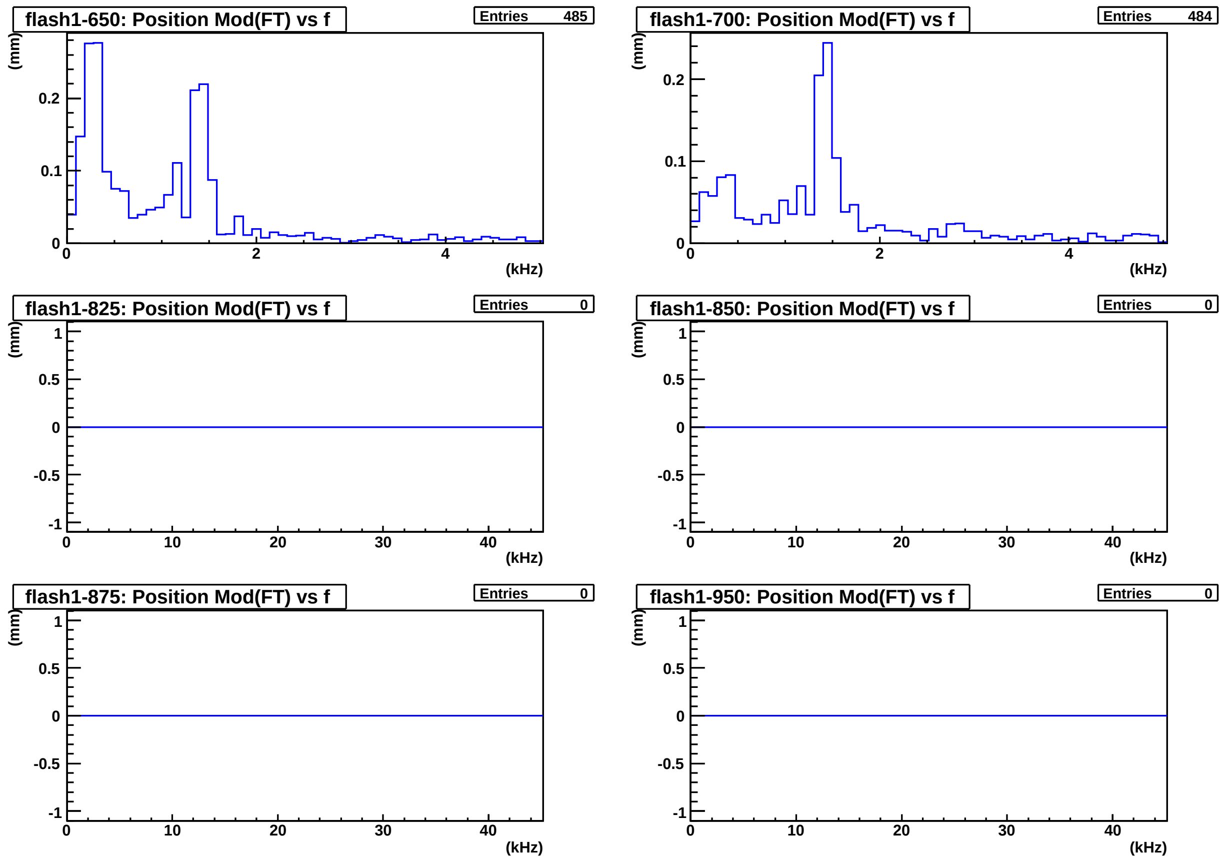

Figure 18: Detail of Figure 14. The magnitude of the Fourier transform of the position for flash 1 for the six different house delays; the delay is encoded in the histogram title. Only points with a sum signal above 100 EU were included in the transform. The mean value of the position signal was subtracted before computing the Fourier transform.

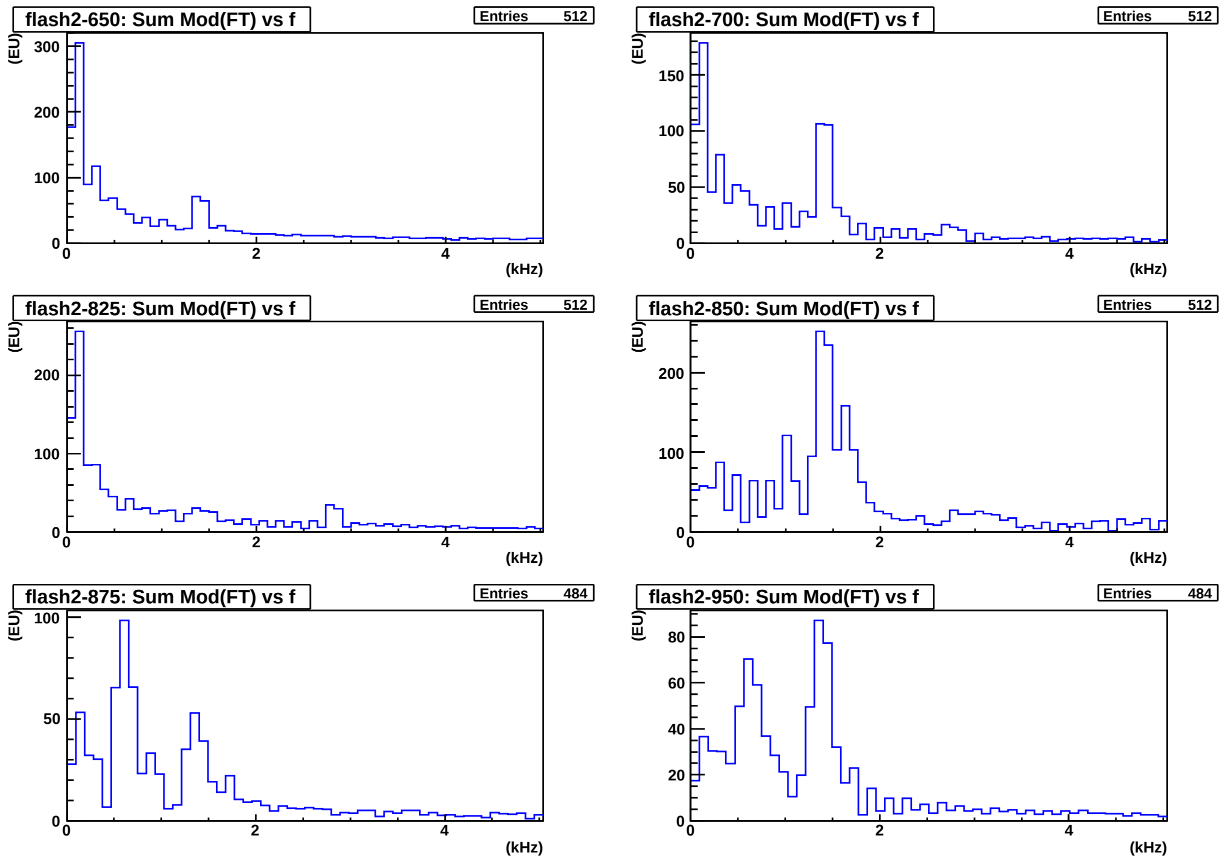

Figure 19: Detail of Figure 15. The magnitude of the Fourier transform of the sum signal for flash 2 for the six different house delays; the delay is encoded in the histogram title. Only points with a sum signal above 100 EU were included in the transform. The mean value of the sum signal was subtracted before computing the Fourier transform.

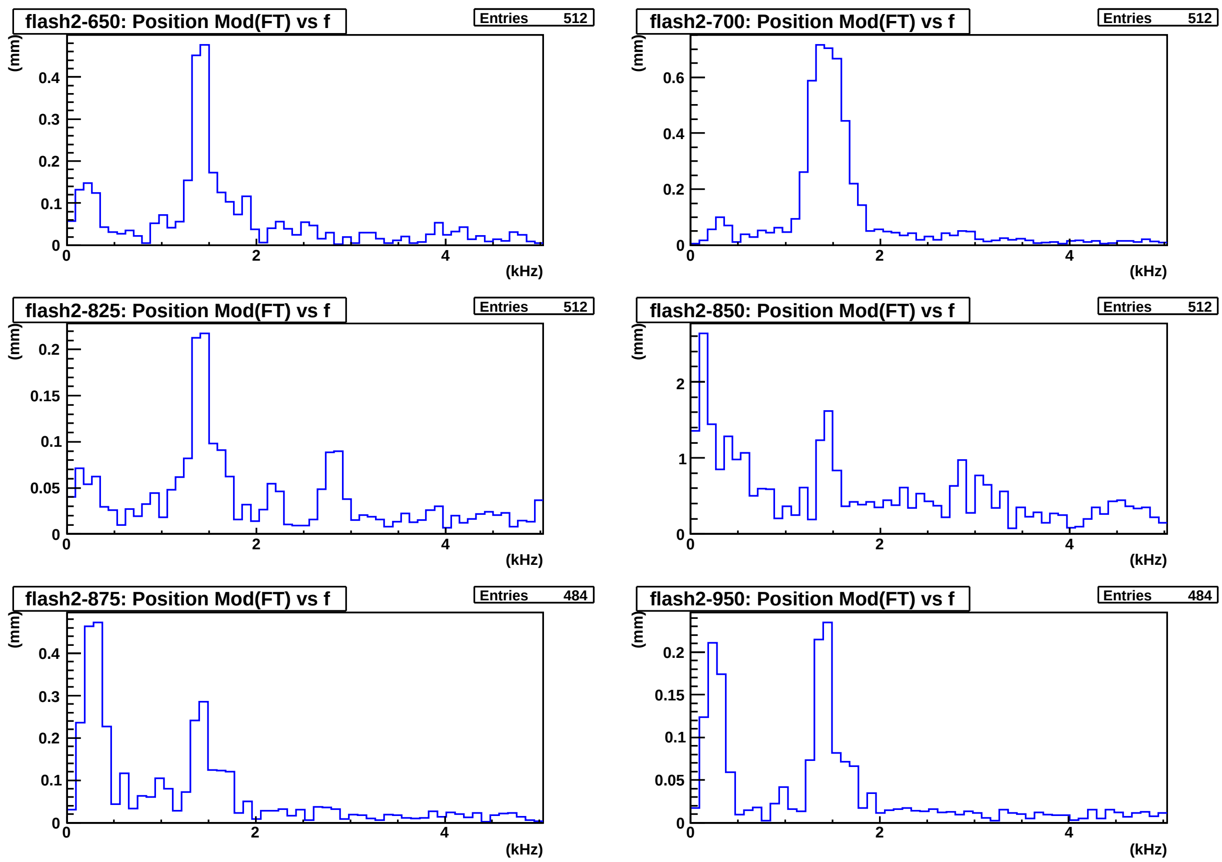

Figure 20: Detail of Figure 16. The magnitude of the Fourier transform of the position for flash 2 for the six different house delays; the delay is encoded in the histogram title. Only points with a sum signal above 100 EU were included in the transform. The mean value of the position signal was subtracted before computing the Fourier transform.